Measurement of Thermal Conductivity of Buried Heat Source Concrete and Study of Influence Factors in the Early Age

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***Abstract*-Based on the steady-state method, SK-DR300B plane table thermo-conductivity meter is used to measure the thermal conductivity of the material, detect the thermal conductivity of concrete by simulating the characteristics of heat transmission of the buried hot source concrete and study the impact of water content, temperature and temperature difference on the thermal conductivity of concrete, providing a basis for further obtaining a more realistic method for the estimation of thermal conductivity.**

***Index Terms*-Steady-state Method, Buried Hot Source Concrete, Thermal Conductivity**

I. INTRODUCTION

In recent years, a new construction method of buried hot source concrete in winter has been widely applied to the concrete construction of high-rise buildings in winter. The heat source generally uses a conductive high polymer composite material with a positive temperature coefficient of resistivity (PTC for short) as a strip-like electrical heater of heating elements, that is, self-regulating heating belt. After being electrified, such concentrated exothermic material quickly reaches the design temperature and remains at a constant temperature, and the low-temperature type may reach 65℃. After the heating belt is laid in concrete, a greater temperature difference will be formed with concrete in the entire electrification process [1-2], and the impact of temperature difference on thermal properties of concrete is currently lacking relevant research. Therefore, it is necessary to conduct a thermal performance research under the characteristics of the temperature field, providing an important theoretical design basis for the practical engineering application of the method.

Thermal conductivity is a physical quantity that characterizes the thermal conductance of a material and refers to the quantity of heat per unit area of concrete passed per unit time under each unit of temperature gradient. For different materials, the thermal conductivity is different; for the same material, the thermal conductivity also varies due to a large number of factors influencing the thermal conductivity. For example, the thermal conductivity of concrete is influenced by factors such as material density, water-cement ratio, water content, choice of cement and building stones, stirring and sampling time and degree of vibration, as a result of which the thermal conductivity is greatly different. Existing researches have shown that temperature rise enhances the thermal motion of material molecules, and the thermal conductance of the air in material pores and radiation of pore walls shall be enhanced accordingly. Therefore, the thermal conductivity of the material increases as the material temperature rises, and the thermal conductivity of most materials is a function of temperature. In addition, the thermal conductivity of water is 0.581 kJ/(m·h·℃), which is over 20 times greater than that of static air (0.0256 kJ/(m·h·℃)), so the thermal conductivity of same materials with different water content also varies greatly.

In addition, the internal porosity of concrete keeps increasing while the thermal conductivity decreases with the development of hydration. The existing researches show that the thermal conductivity of hardened concrete is 21%~33% lower than that of unhardened concrete, and Anton Karel Schindler has established the relationship between thermal conductivity and degree of hydration, as shown in Formula (1).

$$\lambda(\alpha)=\lambda_u(1.33-0.33\alpha) \qquad (1)$$

Where, $\lambda(a)$ refers to the thermal conductivity as the degree of hydration is α (kJ/（m·h·℃); λ_u refers to the final thermal conductivity (kJ/（m·h·℃).

Therefore, the thermal conductivity of concrete in the early age is studied with regard to water concrete and temperature according to the characteristics of heat transmission of buried hot source.

II. THERMAL CONDUCTIVITY TEST ON CONCRETE

A Test overview

In this paper, the influence law of water content and temperature on the thermal conductivity of buried heat source concrete in the early age is studied through laboratory tests.

1. Test design

This test mainly studies the influence of water content, temperature and degree of hydration on the thermal conductivity of buried heat source concrete in the early age. Therefore, the test is divided into two parts, one part is the influence of water content on thermal conductivity, including the same degree of hydration, the influence of water content on thermal conductivity, different degree of hydration as well as the influence of water content on thermal conductivity; the other part is the influence of temperature on thermal conductivity in case of same degree of hydration.

According to the fact that the amount of thermal conductivity Q through plate is proportional to the temperature difference Δt of both sides of the plate in one-dimensional steady state, proportional to the plate thickness d and proportional to thermal conductivity λ, the steady-state plate method is used to determine the thermal conductivity of material, so as to determine the thermal conductivity of material and temperature and its relationship with temperature and water content. That is, the stable amount of thermal conductivity that passes thin-wall plate (wall thickness is less than 1/10 of wall length and width) is shown below:

$$Q = \frac{\lambda}{d} \Delta t A \tag{2}$$

Where, Q refers to amount of thermal conductivity (W); Δt refers to the temperature difference between both sides of the plate (℃); d refers to plate thickness (m); A refers to the area of thermal conductivity in the direction vertical to heat flow (m2).

Thermal conductivity is obtained according to the Formula above:

$$\lambda = \frac{Qd}{\Delta t A} \tag{3}$$

Water content includes mass water content and volume water content, of which mass water content is ω_z, which refers to the ratio of material water content and mass of dry test piece, that is,

$$\omega_z = \frac{g_1 - g_2}{g_2} \times \% \tag{4}$$

Where: g_1 refers to the weight of test piece of wet material (kg); g_2 refers to the weight of dry material (kg).

Volume water content ω_d refers to the ratio of water content volume of test piece and test piece volume, that is:

$$\omega_d = \frac{V_1}{V_2} \times \% \tag{5}$$

Where: V_1 refers to the volume of test piece water (m3); V_2 refers to the volume of test piece (m3)

The relationship between mass water content and volume water content is:

$$\omega_z = \frac{1000 \cdot \omega_d}{\rho_\mathrm{d}} \tag{6}$$

Therefore, it can be known that mass water content is linearly related to volume water content only, and the water content mentioned in equipment collection and Formulas in this paper refers to mass water content.

2 Preparation of test piece

For preparation of test piece, following materials are used, such as P·O 42.5 Portland cement supplied by Shenyang Dunshi, local river sand (medium sand) as fine aggregate, local gravels as coarse aggregate with the particle size of 8~14mm, tap water and 0.2% water reducer (polycarboxylate dry powder), and the matching is shown in Table 1. In addition, the dimensions of the test piece used in the test are 300mm×300m×60mm.

TABLE 1 CONCRETE MIX PROPORTION AND CHEMICAL PROPERTIES OF MATERIALS

Constituent	Cement	Sand	Stone	Water
Mass (kg)	390	673	1222	165
Specific heat (kJ / (kg · °C))	0.456	0.84	0.84	4.187
Thermal conductivity (w/(m·K))	0.29	0.87	1.16	0.581

3 Test equipment

The thermal conductivity is tested using SK-DR300B plane table thermo-conductivity meter provided by Wuhan Shengke Technology Development Co., Ltd. The equipment uses the steady-state method to measure the thermal conductivity of material and the executive standard of the equipment is GB/T10294-2008 Thermal Insulation - Determination of Steady-state Thermal Resistance and Related Properties - Guarded Hot Plate Apparatus, of which the steady-state thermal resistance and related properties of insulating materials are determined using the guarded hot plate apparatus with dual test pieces. Range of measurement: 0.015~3 W/(m•K), measurement accuracy: <±2%; range of measurement: 0°C to +70°C (average temperature), measurement accuracy: 0.05°C, as shown in Figure 2.7

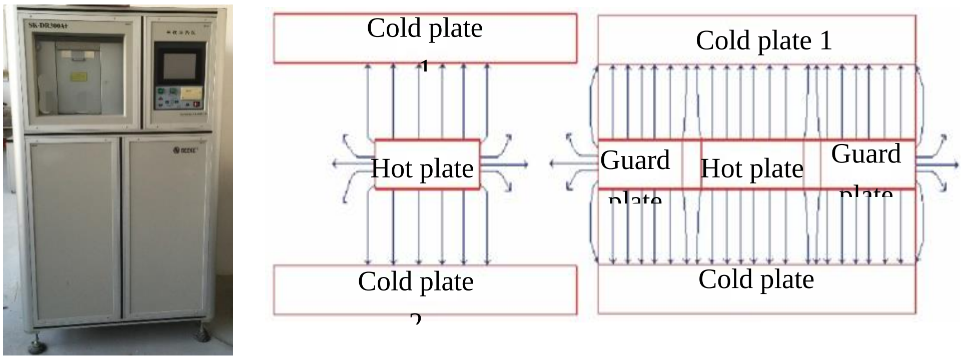


Figure 1 SK-DR300B Plane Table Thermo-Conductivity Meter and Principles of Heat Transmission

4 Measurement content and method

Based on the concept of degree of hydration, concrete with same matching in the same age under different curing temperatures has different degrees of hydration, so two curing systems are adopted in the test. Curing system 1 is to take the test pieces at the age of 3d, 7d and 28d for curing at constant temperature of 45℃; curing system 2 is to take test pieces at the age of 3d, 7d and 28d for curing at constant temperature of 65℃ for the study of thermal conductivity test, and the preparation process of test pieces are shown below.

(a) Prepare test pieces according to concrete mix proportion and then put them in thermostat for curing.

(b) Different water content: Under the same water-cement ratio of concrete, water content has a great influence on the thermal conductivity of concrete. Therefore, put 4 groups of test pieces of each kind under two curing systems after reaching the test age in the oven (60℃) for baking different periods of time, and make it have 4 kinds of water content, of which one group of test pieces shall be baked to constant weight, and then take them out and separately weigh, calculate water content according to Formula 2.46 and measure its thermal conductivity. In addition, the test pieces are grouped in Table 2.

TABLE 2 GROUPING OF TEST PIECES

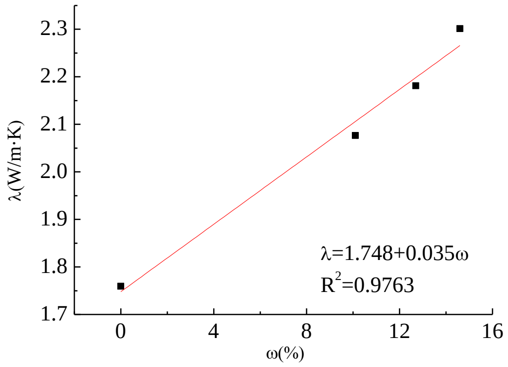
Curing temperature (℃)	Curing time (d)	Number of each pair of test pieces	Quantity of test pieces (pair)
45	3	3A, 3B, 3C, 3D	4
	7	7A, 7B, 7C, 7D	4
	28	28A, 28B, 28C, 28D	4
65	3	3E, 3F, 3G, 3H	4
	7	7E, 7F, 7G, 7H	4
	28	28E, 28F, 28G, 28H	4

(c) Temperature: The relationship between temperature and thermal conductivity is very complicated. Under normal circumstances, the thermal motion of material molecules enhances as temperature rises, the radiation and heat exchange between the air and the pore walls inside the porous medium enhances and the thermal conductivity increases in succession. Therefore, the test simulates the influence of the internal temperature gradient of buried hot source concrete in the early age on thermal conductivity while taking into account the influence of temperature on the thermal conductivity of material, and simulates temperature gradient by changing the temperature of cold and hot plates of plane table thermo-conductivity meter.

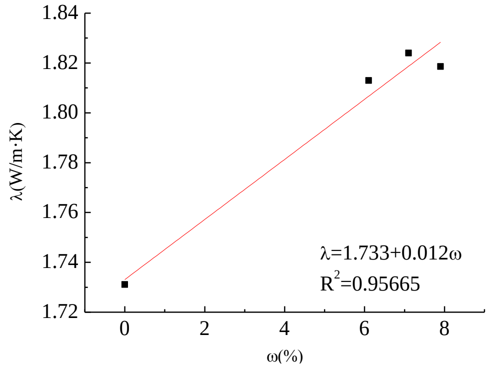
B Analysis of test results

1 Influence of water content on thermal conductivity

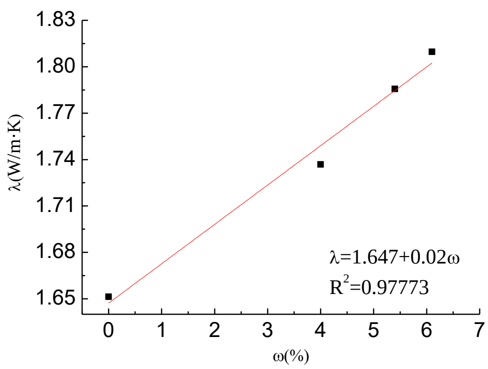
The test simulates the thermal conductivity of the concrete with different water content in different areas in the early age, and draws the curve of the relationship between water content and thermal conductivity in the same age under different curing systems, as shown in Figure 2.



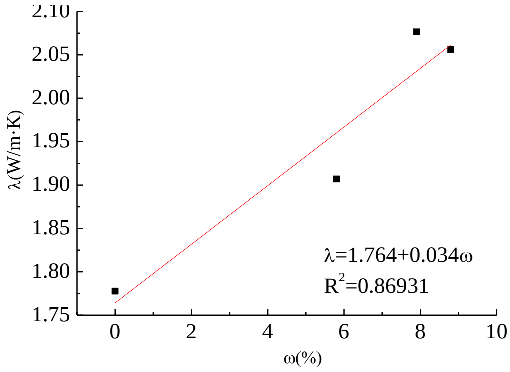
(a) Relationship between water content and thermal conductivity after curing for 3d at 45℃



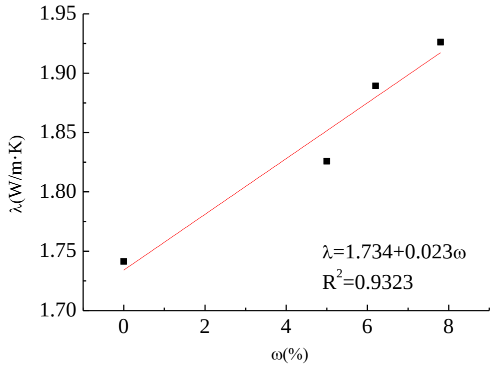
(b) Relationship between water content and thermal conductivity after curing for 7d at 45℃



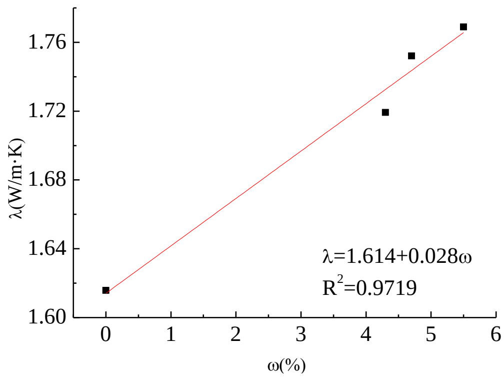
(c) Relationship between water content and thermal conductivity after curing for 28d at 45℃



(d) Relationship between water content and thermal conductivity after curing for 3d at 65℃



(e) Relationship between water content and thermal conductivity after curing for 7d at 65℃



(f) Relationship between water content and thermal conductivity after curing for 28d at 65℃

Figure 2 Curve of Relationship Between Water Content and Thermal Conductivity

From Figure 2, it can be seen that the thermal conductivity of water-bearing components under two curing systems is greater than that of dry concrete components, and there is a linear relationship between water content and thermal conductivity, which can be expressed as Formula 1

$$\lambda_w = \lambda_d + \xi_\lambda \omega \tag{7}$$

Where: ξ_λ refers to the increment of thermal conductivity of water content for increase of 1%.

In addition, we've found after comparing the concrete under two curing conditions of 45℃ and 65℃ that the thermal conductivity of concrete after curing for 3d at 65℃

is higher than that of curing 3d at 45℃, and the thermal conductivity under the two conditions will be reduced with the development of age, but after curing 28d, the thermal conductivity of concrete cured at 65℃ is lower than that of concrete cured at 45℃.

2 Influence of temperature on thermal conductivity

(1) Influence of average temperature on thermal conductivity with same temperature difference

With regard to the same temperature difference of 20℃, different average temperature conditions are shown in Table 3, and the thermal conductivity of concrete will be determined at the age of 3d.

TABLE 3
RELATIONSHIP BETWEEN AVERAGE TEMPERATURE AND THERMAL CONDUCTIVITY WITH SAME TEMPERATURE DIFFERENCE

S.N.	1	2	3	4
Cold plate (°C)	15	25	35	45
Hot plate (°C)	35	45	55	65
Temperature difference (°C)	20	20	20	20
Average temperature (°C)	25	35	45	55
Thermal conductivity (w/(m·K))	1.7592	1.7657	1.7895	1.792

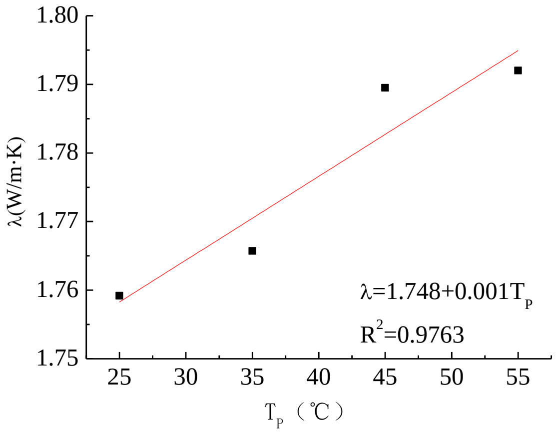


Figure 3 Relationship Between Average Temperature and Thermal Conductivity with Same Temperature Difference

It can be seen from Figure 2.9 that the temperature difference between cold and hot plates is 20℃ when the concrete test piece is at the curing age of 3d at 45℃, thermal conductivity rises with the increase in average temperature of cold and hot plates and the linear relationship of test data fitting is shown in Figure 2.9, from which it can be seen that average temperature is linearly related to thermal conductivity as average temperature varies with the same temperature difference. In addition, such relationship may be expressed as Formula 2.50.

$$\lambda_T = \lambda_0 + \xi_T T_p \qquad (8)$$

Where: λ_T refers to the thermal conductivity of test piece as average temperature is T (w/(m·K)); λ_0 refers to the thermal conductivity of test piece as average temperature is 0 (w/(m·K)); ξ_T refers to the increment of thermal conductivity as average temperature of material increases by 1℃; T_p refers to average temperature (℃).

(2) Relationship between temperature difference and thermal conductivity with same average temperature

With regard to the same temperature difference of 35℃ and different average temperature conditions, the thermal conductivity of concrete will be determined at the age of 3d at 45℃, as shown in Table 2.10.

TABLE 4
VALUE OF THERMAL CONDUCTIVITY WITH SAME AVERAGE TEMPERATURE AND DIFFERENT TEMPERATURE DIFFERENCE

S.N.	1	2	3
Cold plate (°C)	5	15	25

Hot plate (°C)	65	55	45
Temperature difference (°C)	60	40	20
Average temperature (°C)	35	35	35
Thermal conductivity (w/(m·K))	1.7707	1.7651	1.7428

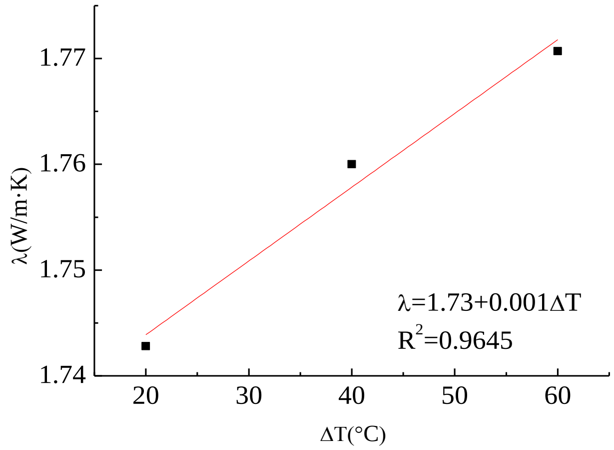


Figure 4 Relationship Between Temperature Difference and Thermal Conductivity with Same Average Temperature

From Figure 4, it can be seen that the thermal conductivity rises with the increase in temperature difference between cold and hot plates, and its linear relationship of test data fitting is shown in Formula below

$$\lambda_{\Delta T} = \lambda_1 + \xi_{\Delta T} \cdot \Delta T \quad (9)$$

Where: $\lambda_{\Delta T}$ refers to the thermal conductivity of test piece as average temperature is ΔT (w/(m·K)); λ_1 refers to the thermal conductivity of test piece as average temperature is 0 (w/(m·K)); $\xi_{\Delta T}$ refers to the increment of thermal conductivity as average temperature of material increases by 1℃; ΔT refers to average temperature (℃).

(3) Simulation of hot plate temperature at 65℃ for heat transmission of heating belt

With regard to hot plate temperature of 65℃ and different cold plate temperature conditions, simulate the heat transmission of heating belt to concrete and determine the thermal conductivity of concrete at the age of 3d, 5d and 7d, as shown in Table 5.

TABLE 5 VALUE OF THERMAL CONDUCTIVITY OF HEAT TRANSMISSION SIMULATED FOR HEATING BELT

S.N.	1	2	3
Cold plate	5	25	45
Hot plate	65	65	65
Temperature difference	60	40	20
Average temperature	35	45	55
Thermal conductivity at the age of 3d	1.7607	1.7581	1.7358
Thermal conductivity at the age of 5d	1.7293	1.6925	1.6683
Thermal conductivity at the age of 7d	1.6637	1.6547	1.6387

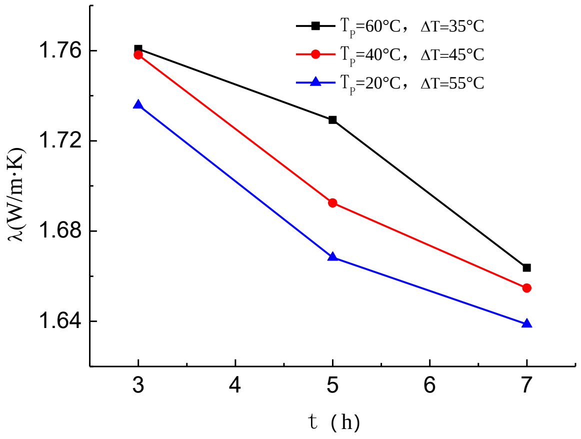


Figure 5 Changes in Thermal Conductivity of Heat Transmission Simulated for Heating Belt

From Figure 5, it can be seen that the thermal conductivity rises with the increase in temperature difference between cold and hot plates, and the influence of temperature difference between cold and hot plates is greater than that of average temperature on thermal conductivity.

Therefore, this paper gives the Formula for the estimation of thermal conductivity of concrete by taking into account the influence of concrete temperature, water content and degree of hydration based on the test

$$\lambda = \lambda_u (1.33 - 0.33a) + \xi_{\Delta T} \frac{\partial T}{\partial x_i} + \xi_\lambda w \tag{10}$$

Where, the thermal conductivity is determined through test. In this paper, $\xi_{\Delta T}$ is 0.033 and ξ_λ is 0.035.

III Conclusion

The thermal conductivity of buried heat source concrete is tested in this paper. According to the characteristics of temperature field of the buried heat source concrete and based on the steady-state flat band method test principle and measurement technology, influence factors that result in the difference in thermal conductivity of materials are proposed, and the relationship between the thermal conductivity of buried hot source concrete and water content, temperature and other factors is given based on the test.

(1) SK-DR300B plane table thermo-conductivity meter based on the steady-state flat band method test principle meets the high accuracy test requirements of material test study for thermal conductivity of materials, which is applicable due to its high degree of automation and stable performance.

(2) The linear Formula of thermal conductivity by taking into account water content is proposed in the test, which reflects the influence of water content on thermal conductivity of concrete and establishes a relationship between the two, indicating that there is a certain difference in thermal conductivity in case of different water content.

(3) The relationship between thermal conductivity and temperature is given and the empirical formulas of influence of average temperature and temperature difference are separately given. In addition, it indicates that temperature difference has a greater influence on thermal conductivity than average temperature by comparing the influence of temperature difference and average temperature on thermal conductivity of concrete by test.

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